ELECTRIFICATION OF CANADIAN NORTHERN COMMUNITIES, USING LOW EMISSION MICROGRIDS

3/30/2021

Mehrdad Pirnia, Enrique Gabriel Vera, Claudio Canizares

UNIVERSITY OF WATERLOO | FACULTY OF ENGINEERING

Outline

- Electrification in Remote Communities (RCs)
- Electrification models for RCs
- Microgrid (MG) planning model
- Model assumptions
- Scenarios
- Case Study
- Contributions
- Future work

RC Electrification

PROBLEM

- Electrification of RC highly dependent on fossil fuels.
- High electricity rates: transportation costs, no access to bulk power system.
- Low flexibility and reliability.
- High GHG emissions.

CHALLENGES

Geographical location, extreme weather conditions, consumption patterns, and availability of energy source.

SOLUTION

Deployment of MGs with Renewable Energy Resources (**RES**) and Energy Storage Systems (**ESS**).

RES MGs

- Based on a wide variety of Distributed Energy Resources (**DERs**), which include **RES** and **ESS**.
- Provide access to **cheaper**, **cleaner** and more **flexible** and **reliable** electricity.

MG Electrification Models

Model and its outcomes

- Plan an appropriate energy supply mix to satisfy electricity demand in RCs.
- Advocate decarbonized electrification in RC MGs using **RES** and **ESS.**
- Support Canada in meeting zero emissions target by prioritizing the **reduction of GHG emissions**.
- Identify the optimal (most economic) size and mixture of the generation resources, and the time of their deployment.

Gap Filling

- From a planning perspective, the model allows quantifying the potential benefits of MGs with RES and ESS, promoting their adoption for **RC MGs decarbonization.**
- Gap addressed is the inclusion of **hydrogen systems** as part of the ESS technologies considered in the planning process.

MG Planning Model

Type of Mathematical Model

Optimization model involving an **objective function**, a set of **parameters**, decision **variables**, and technical, economical, and/or environmental **constraints**.

Objective

Minimize: Net Present Cost (NPC) of total costs, including capital, and O&M costs.

Variables

- **Binary:** Hourly on/off status of diesel generators, charging and discharging status of batteries and hydrogen storage systems, and purchase of new diesel generators.
- **Integer:** Investments in RES capacities (except solar) .
- **Continuous:** Generation power output, SOC of batteries and hydrogen storage systems.

Inputs

- **Estimated parameters:** Electricity demand and RES availability.
- **Technical** and **economical parameters**.

MG Planning Model

Outputs

- **NPC of Investment:** For new diesel generators, RES, and ESS.
- **NPC of Operation and Maintenance:** For new and existing diesel generators, RES, and ESS.
- **NPC of Fuel Costs:** For diesel generators.
- **Fuel Consumption:** For diesel generators.
- **Yearly Capacity additions:** For new diesel generators, RES, and ESS.
- **Total Savings.**
- **GHG emissions reduction.**

MG Planning Model

Objective Function

Includes all the NPC Costs: Capital, Operation and Maintenance, and Fuel costs.

Constraints

- Represent the hourly operation of the RC MG.
- Decide the times and sizes of the capacities needed in the long term for diesel, RES, and ESS.

a) Commissioning of new generation (diesel, RES, and ESS).
b) Supply-demand balance.
c) Operating reserves.
d) Diesel generator limits.
e) Diesel generator service life.
f) Diesel generator availability.
g) Available solar power generation.
h) Available wind power generation.
i) Battery SOC and limits.
j) Hydrogen system (hydrogen tank, electrolizer, fuel cell).

MG Planning Model Solution

Software	General Algebraic Modelling System (GAMS).
Solver	CPLEX; since model is a Mixed Integer LINEAR Programing (MILP) problem.
Hardware	Server with: • Processor: Inter(R) Xeon(R) CPU. • Operating System: Windows 64-bit. • RAM: 256 GB.
Code	Available upon request

Study Case: Sanikiluaq

- This is a community located in Nunavut.
- Only permanent settlement where nearly 800 people reside.
- Types of consumption: residential and institutional electricity.
- Type of generation: 100% diesel.
- Type of electricity grid: not connected to a power system or other MGs (isolated RC MG).

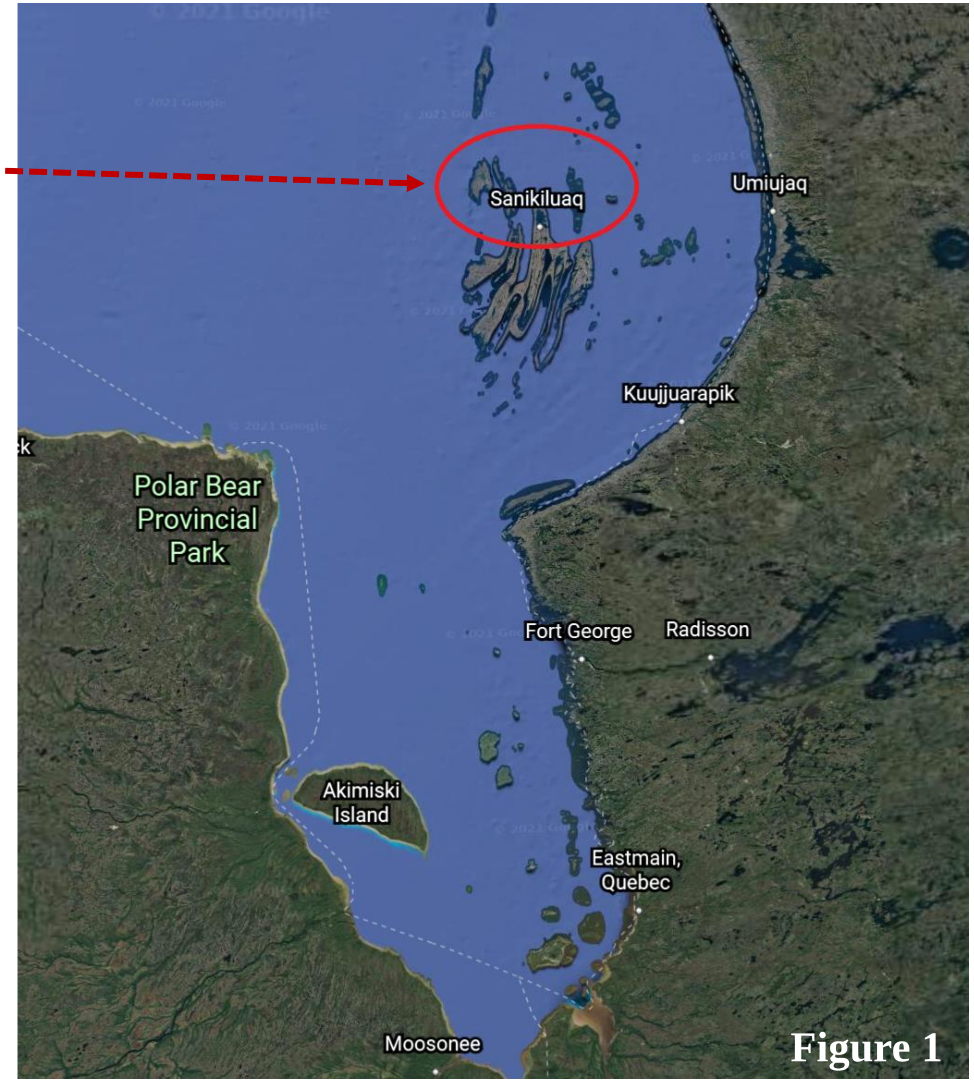


Figure 1

Assumptions

Time	Simplification for simulations: A representative day of each month is considered 288 hours are used: 24 hours x 12 days.
Economical Parameters	• Discount rate (*d*) : 8%. • Cost of Diesel: 2.391 ($/l).
Windows for Investment	• RES and ESS: First 5 years. • Diesel: Between 3rd and 10th year.
Technical Parameters	• Reserves: 50% for wind, 25% for solar, and 10% for load. • Ramping up/down: not considered, generators can turn on/off in fractions of 1 hour. • Temperature at standard conditions: 25 °C. • Continuous charging/discharging: 4 hours. • Load grow: 1%/year. • Minimum load for diesel generators: 40%
Inclusion of RES	• At least 1 hydrogen system. • 1% of annual energy supplied by solar and/or wind

Scenarios

Base Case	Business as usual, operation based on diesel generators.
1A	D+S+W+B+H: Diesel (D) + Solar (S) +Wind(W)+Batteries (B) + Hydrogen (H).
2A	D+S+W+H: No Batteries.
3A	D+S+W+B: No Hydrogen.
4A	S+W+B+H: No Diesel, operation only with RES and ESS.
1B	D+W+B+H: Diesel (D) + Wind(W)+Batteries (B) + Hydrogen (H).
2B	D+W+H: No Batteries.
3B	D+W+B: No Hydrogen.
4B	W+B+H: No Diesel, operation only with RES and ESS.

Input Data

- Demand:

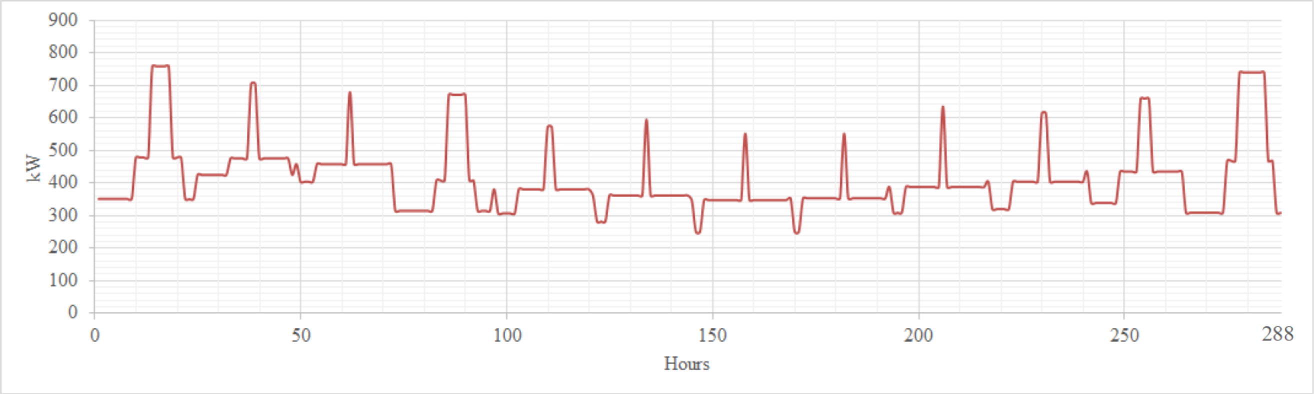


Figure 2: Sanikiluaq yearly average load profile [6].

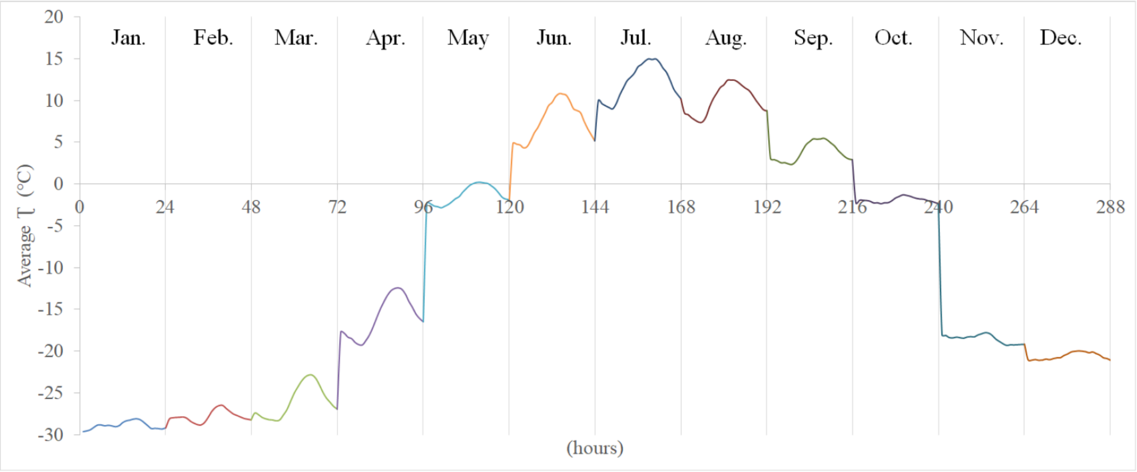
- Solar Panels: A continuous variable.

Cost ($/kW)	O&M ($/kWh)	α (p.u./$°C$)	GT^{STC}	df	Lifetime
5,082	0.0145	-0.041	1 kW/m^2	98%	20 years

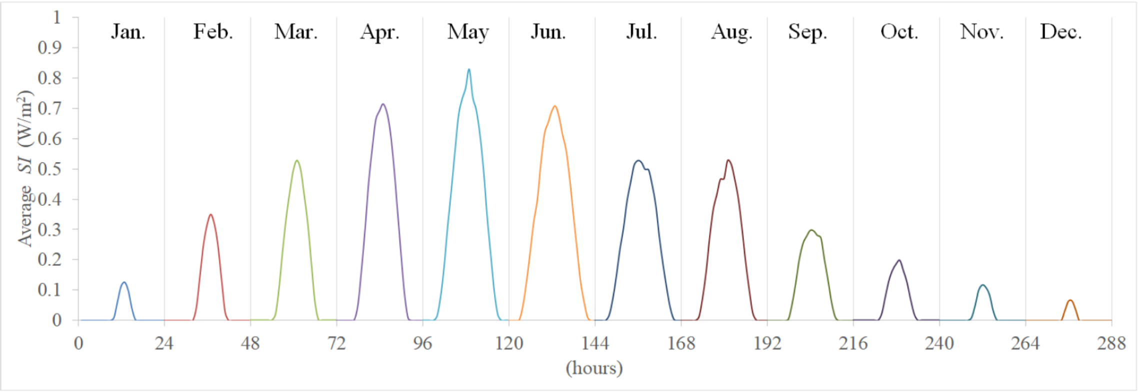
Table 1: Parameters and costs for solar panels at Sanikiluaq.

Input Data

- Solar cell temperature and monthly Solar Irradiation.



a)



b)

Figure 3: Sanikiluaq's monthly average (a) temperatures τ and (b) solar irradiation SI [6].

UNIVERSITY OF WATERLOO | FACULTY OF ENGINEERING

Input Data

- New diesel generators:

Fuel Consumption Curves

Gen.	Capacity (kW)	O&M ($/kWh)	Lifetime (h)	Cost ($/$kW$)	a ($l/h/kW^2$)	b ($l/h/kW$)	c (l/h)
1	320	0.0191	100,000	727	-0.0002	0.3287	3
2	520	0.0191	100,000	727	-0.00003	0.2227	10.3

Table 2: New diesel generator parameters and costs.

- Existing diesel generators:

Fuel Consumption Curves

Gen.	Capacity (kW)	O&M ($/kWh)	Lifetime (h)	a ($l/h/kW^2$)	b ($l/h/kW$)	c (l/h)
1	330	0.0218	35,339	-0.0006	0.5212	-15
2	330	0.0218	21,600	-0.0006	0.5212	-15
3	330	0.0218	14,400	-0.0006	0.5212	-15
4	330	0.0218	7,200	-0.0006	0.5212	-15
5	500	0.0218	64,696	0.00003	0.2105	10.3
6	540	0.0218	68,820	0.00003	0.2144	10.3
7	550	0.0218	100,000	0.00003	0.2105	10.3

Table 3: Main generators' characteristics at Sanikiluaq.

Input Data

- Existing diesel generators stand-by modes:

	Year of Project Horizon																			
Gen.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1		*		*		*		*		*		*		*		*		*		*
2		*		*		*		*		*		*		*		*		*		*
3	*		*		*		*		*		*		*		*		*		*	
4	*		*		*		*		*		*		*		*		*		*	
5	*		*		*		*		*		*		*		*		*		*	
6	*		*		*		*		*		*		*		*		*		*	
7		*		*		*		*		*		*		*		*		*		*

Table 4: Existing diesel generators in stand-by mode (*).

Input Data

- Wind Turbines and Wind Data: Wind generators with **250 kW of nominal capacity** were considered.

Cost ($/kW)	O&M ($/kWh)	Cut-in Speed	Nominal Speed	Cut-out speed	Lifetime
7,943	0.0363	2.5 m/s	7.5 m/s	25 m/s	20 years

Table 5: Parameters and costs of wind generators.

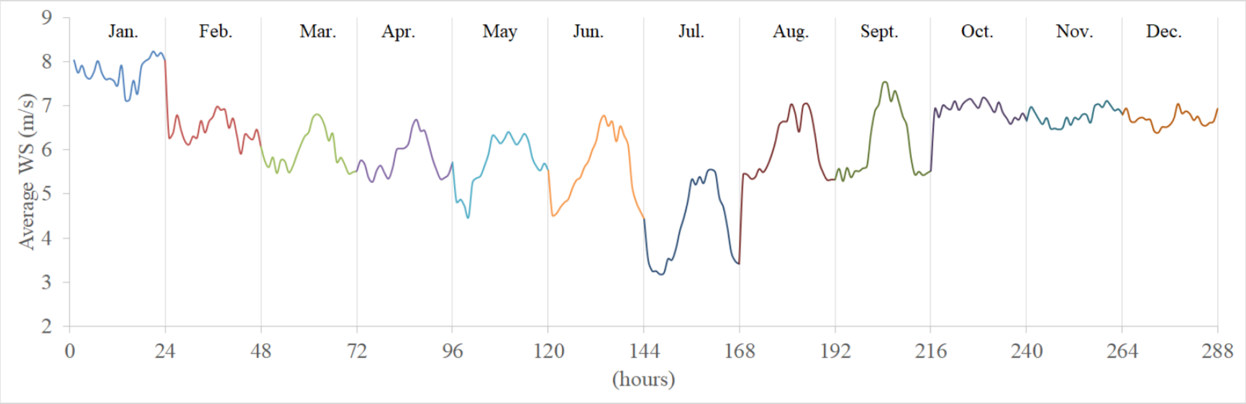


Figure 4: Average wind speed WS at 21m hub height [6].

Input Data

- Battery modules: **Li-ion batteries** with **100 kWh and 20 kW** peak power of charge/discharge.

Cost ($/kWh)	O&M ($/kWh)	SOC_0	DoD	η_{Ch}	η_{DCh}
1,504	0.0069	50%	20%	95%	95%

Table 6: Parameters and costs of batteries.

Input Data

- Hydrogen System: **Fuel cells, electrolyzer**, and a **hydrogen tank**.

Capacity (kW)	Cost ($/u)	O&M ($/h)	η_{FC}	Lifetime (h)
250	168,581	2	60%	50,000

Table 7: Parameters and costs of fuel cells.

Capacity (kW)	Cost ($/u)	O&M ($/y)	η_E	Lifetime (y)
330	1,279,000	194	70%	15

Table 8: Parameters and costs of electrolizer.

Capacity (kg)	Cost ($/u)	O&M ($/h)	HHV	l_C	Lifetime (y)
200	249,745	12,400	39.4 kWh	0.02 p.u.	25

Table 9: Parameters and costs of the hydrogen tank.

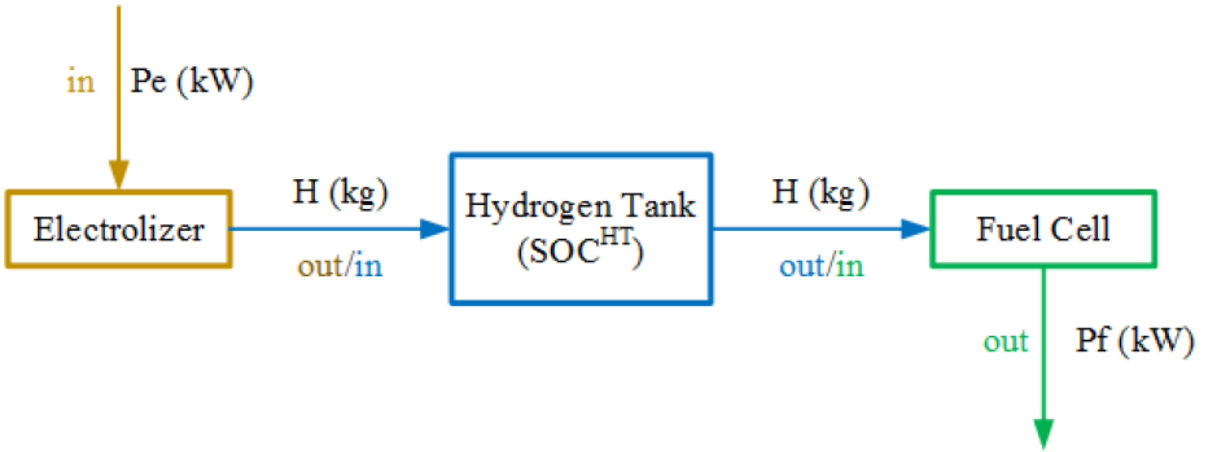


Figure 5: Schematic representation of hydrogen system.

Planning Results

Case		Capacity Additions Diesel (kW)	Solar (kW)	Wind (kW)	Batteries (kWh/kW)	Fuel Cells (kW)	Hydrogen Tank (kg)	Electrolizer (kW)	GHG Red. (%)
Only Diesel									
1A	D+S+W+B+H	0	264	750	800/160	250	200	990	85.8%
2A	D+S+W+H	0	92	1000		250	400	1320	93.2%
3A	D+S+W+B	0	431	500	1800/360				64.3%
4A	**S+W+B+H**	0	577	1000	1000/200	500	200	660	100%
1B	D+W+B+H	320		1000	200/20	250	400	1320	86.1%
2B	D+W+H	0		1000		250	400	1320	93.5%
3B	D+W+B	840		500	1900/380				51.9%
4B	**W+B+H**	0		1250	3900/780	500	200	660	100%

Table 10: Total Capacity additions during the planning horizon.

GHG reductions in all cases

100% RES penetration and operation is possible

Best total GHG and savings

Case		Net Present Costs Fuel Cost (M$)	O&M Diesel Gen. (M$)	Investment (M$)	RES and ESS O&M (M$)	Total Cost (M$)	
Only Diesel		24.87	0.89			25.76	
1A	D+S+W+B+H	3.06	0.11	11.54	3.49	18.19	-29%
2A	D+S+W+H	1.77	0.06	11.94	3.55	17.32	-33%
3A	D+S+W+B	9.12	0.32	8.52	3.19	21.15	-18%
4A	**S+W+B+H**	0.00	0.00	16.57	4.62	21.19	-18%
1B	D+W+B+H	1.64	0.06	11.87	3.54	17.11	-34%
2B	D+W+H	1.76	0.06	11.53	3.43	16.78	-35%
3B	D+W+B	11.97	0.40	6.55	2.71	21.63	-16%
4B	**W+B+H**	0.00	0.0	19.20	6.60	25.80	+0.2%

Savings can be achieved

Table 11: Associated Costs.

Contributions

Supports Canada in meeting zero emissions target

Electrification and Decarbonization

- Guarantees the fulfillment of the electricity needs of the inhabitants of the RCs (supply – demand constraint).
- Reduces uncertainty related to the prices of fossil fuels.

Integrating RES and ESS

- Promotes reduced use of fossil fuels and reduces GHG emissions (51 – 100%) → Benefits Canadian economy
- Enhances electric grid flexibility. → More types of generation technologies

Contributions

Policy Design

Policies aligned with **energy sustainability** and affordability for RCs in Canada.

The model facilitates consideration of **environmental, economical, and community factors.**

As part of a National Platform

The model can be used by **experts**, **researchers**, **investors**, and **policymakers**.

The model helps to determine: Requirements for **financing**, **construction**, **management,** and real time **operation** of RC MGs.

Create products, services, and strategies that help mitigate and solve energy related public problems for RCs

Future work

- Apply the model to address the needs of RCs in Canada.
- Consider more sophisticated methods to incorporate uncertainties in the proposed model.
- Test reliability of different generation mixes.

References

[1] E. Vera, C. Canizares, and M. Pirnia, "Renewable Energy Integration in Canadian Remote Community Microgrids. The feasibility of hydrogen and gas generation," *IEEE Electrification Magazine*, vol. 8, no. 4, pp. 36–45, December 2020.

[2] H. Farhangi and G. Joos, *Microgrid Planning and Design: A Concise Guide*, 1st ed. Wiley-IEEE Press, 2019.

[3] J. Knowles, "Power Shift: Electricity for Canada's remote communities," *Ottawa: The Conference Board of Canada*, 2016. [Online]. Available: https://www.conferenceboard.ca/e-library/abstract.aspx?did=8249

[4] F. Delfino, R. Procopio, M. Rossi, S. Bracco, M. Brignone, and M. Robba, *Microgrid Design and Operation*. Boston, London: Artech House, 2018.

[5] C. Canizares and I. Das, "Feasibility studies of variable speed generators for Canadian Arctic Communities," *WISE*, 2017.

[6] I. Das and C. A. Cañizares, "Renewable Energy Integration in Diesel-Based Microgrids at the Canadian Arctic," *Proceedings of the IEEE*, vol. 107, no. 9, pp. 1838–1856, Sep. 2019.

[7] D. Olivares, "An Energy Management System for Isolated Microgrids Considering Uncertainty," Ph.D. dissertation, University of Waterloo, 2014.

[8] GAMS Development Corp. Gams documentation center. [Online]. Available: https://www.gams.com/latest/docs/

[9] M. Arriaga, C. A. Caizares, and M. Kazerani, "Long-term renewable energy planning model for remote communities," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, pp. 221–231, 2016.

[10] A. Dane and L. Doris, "Alaska Strategic Energy Plan and Planning Handbook." National Renewable Energy Laboratory, 2013.

[11] A. Kanduth, J. Moorhouse, and D. Beugin, "CANADA'S NET ZERO FUTURE: Finding our way in the global transition." Canadian Institute for Climate Choices, 2021.

[12] Canadian Institute for Climate Choices, "Canada's net zero future: Finding our way in the global transition," 2021.

[13] A. Khodaei, S. Bahramirad, and M. Shahidehpour, "Microgrid planning under uncertainty," *IEEE Transactions on Power Systems*, vol. 30, no. 5, pp. 2417–2425, Sep. 2015.

[14] S. P. Burger, J. D. Jenkins, S. C. Huntington, and I. J. Perez-Arriaga, "Why distributed?: A critical review of the tradeoffs between centralized and decentralized resources," *IEEE Power and Energy Magazine*, vol. 17, no. 2, pp. 16–24, Mar. 2019.

[15] A. Ehsan and Q. Yang, "Stochastic investment planning model of multi-energy microgrids considering network operational uncertainties," in *2018 China International Conference on Electricity Distribution (CICED)*, Sep. 2018, pp. 2583–2587.

References

[16] J. Bisschop, *AIMMS Modelling Guide*. AIMMSB.V., 2021.

[17] C. Bataille, D. Sawyer, and N. Melton, "Pathways to deep Decarbonization in Canada." Sustainable Development Solutions Network (SDSN) and Institute for Sustainable Development and International Relations (IDDRI), 2015.

[18] World Energy Council, "WORLD ENERGY TRILEMMA INDEX 2020," 2020.

[19] M. Arriaga, C. A. Canizares, and M. Kazerani, "Renewable energy alternatives for remote communities in northern ontario, canada," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 3, pp. 661–670, 2013.

[20] Municipality of Sanikiluaq. [Online]. Available: http://www.sanikiluaq.ca

[21] M. Gascó-Hernández, *Open Government*, ser. Public Administration and Information Technology. Springer, New York, NY, 2014.

[22] NASA. Prediction of worldwide resources. [Online]. Available: https://power.larc.nasa.gov

UNIVERSITY OF WATERLOO

FACULTY OF ENGINEERING

YOU+WATERLOO

Our greatest impact happens together.